Eur. J. Wood Prod. (2014) 72:635–642
DOI 10.1007/s00107-014-0822-8

ORIGINAL

Value optimized log rotation for strength graded boards using computed tomography

Anders Berglund · Erik Johansson · Johan Skog

Received: 16 July 2013 / Published online: 13 August 2014

Abstract A possible application for an industrial computed tomography scanner in a sawmill is finding an optimal rotational position of logs with respect to knots and outer shape. Since a computed tomography scanner is a great investment, it is important to investigate potential profitability of such an investment for different production strategies. The objective of this study was to investigate the potential value increase of the sawn timber of Norway spruce (*Picea abies* (L.) Karst.) by rotating logs to their optimum position prior to sawing compared with sawing all logs in horns down position. The production strategy evaluated by log breakdown simulation in this case study was to produce strength graded timber of the center boards, while the side boards were appearance graded. This case study showed an average value increase with respect to the value of center boards, side boards and chips of 11 %.

1 Introduction

An industrial computed tomography (CT) scanner for the sawmill industry (Giudiceandrea et al. 2011) raises questions regarding production strategies, and how to increase the profit return when investing in such a scanner. A CT scanner will provide three dimensional information about the inner properties, e.g. knots, of the log available at production speed. One way to utilize this information is to optimize the rotational position of each log that is processed at the saw line. The idea is to find the rotational position of each log that results in highest-value products.

In an earlier work by Berglund et al. (2013), log breakdown was simulated for about 800 Norway spruce (*Picea abies* (L.) Karst.) logs and 600 Scots pine (*Pinus sylvestris* L.) logs from mainly Sweden and Finland, but also France. This made it possible to investigate the profitability in an improved log rotation when using CT data to optimize the rotational position. In that study, all sawn timber was appearance graded according to the Nordic timber grading rules (Swedish Sawmill Managers association 1994). Consideration was given only to knots and wane when determining the board grade. An increased average value recovery of 13 % was found using the log rotation for greatest profit return for each log. An introduced rotational error of the sawing machine reduced the increased average value yield to 6 %.

Some sawmills produce and sell strength graded timber instead of, or in addition to, appearance graded timber. It would be useful to investigate the profitability of using a CT scanner at the saw line to optimize this breakdown process. Since internal features of logs, such as knots, can be detected, there should be a possibility for rotating logs to avoid edge knots and arris knots and thereby increasing the share of high strength boards. Such an investigation would be useful when evaluating whether the results of Berglund et al. 2013 are applicable to sawmills producing strength graded timber or whether the obtained value recovery mainly depends on the grading rules.

When using timber in load-bearing constructions, strength and stiffness of the material have to be within ensured limits (Johansson 2003). Using wood for construction is somewhat different compared with other

A. Berglund (✉) · E. Johansson · J. Skog
Division of Wood Science and Engineering, Department of Engineering Sciences and Mathematics, Luleå University of Technology, Forskargatan 1, SE-931 87, Skellefteå, Sweden
e-mail: anders.1.berglund@ltu.se

E. Johansson · J. Skog
SP Wood Technology, Laboratorgränd 2, SE-931 77, Skellefteå, Sweden

engineering materials such as steel or concrete, where strength and stiffness of the material can more easily be controlled. To control mechanical properties of wood and to ensure dimensional strength of a construction, wood is graded according to grading rules. There are two methods in use to measure board strength, namely *visual strength grading* and *machine strength grading*.

Visual strength grading, as the name implies, ensures that the visible defects on a board do not exceed the limits specified by the grading rule. Visual strength grading in Scandinavia is performed according to the Nordic standard INSTA 142 2009. The Nordic standard pertains to Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* (L.) Karst.), Sitka spruce (*Picea sitchensis* (Bong.) Carr.), Silver fir (*Abies alba* Mill.), Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) and larch (*Larix decidua* Mill., *Larix eurolepis*, *Larix kaempferi* (Lamb.) Carr.). Timber graded according to this standard is sorted into classes T3, T2, T1 and T0.

The objective of this work was to investigate, by log breakdown simulations, how the log rotation affects the value outcome of timber visually strength graded according to the Nordic standard INSTA 142 2009. The production strategy of this case study was from the perspective of a sawmill in northern Sweden processing Norway spruce (*Picea abies* (L.) Karst.) to produce strength graded timber of the center boards, while the side boards are graded according to the appearance grading in the Nordic timber grading rules (Swedish Sawmill Managers association 1994). The reason for grading the center boards by visual grading is that visual grading can be taken into consideration prior to sawing using an industrial CT scanner since internal features like knots can be detected (Johansson et al. 2013).

2 Materials and methods

2.1 The European spruce stem bank

The material used in this study comes from the European spruce stem bank (ESSB) (Berggren et al. 2000), which consists of data from about 800 Norway spruce (*Picea abies* (L.) Karst.) logs. The logs origin from 31 plots in different geographic locations, where the largest share is from Sweden, but also plots from Finland and France are represented.

When collecting these logs, six trees were chosen in each plot; two in a lower diameter class, two in a middle diameter class and two in a larger diameter class. The stems were divided into the diameter classes based on the quadratic mean diameter at breast height of the stand, with class limits at half a standard deviation above and below this mean (Björklund and Moberg 1999). The diversity of the logs in the ESSB with respect to diameter, outer shape and knot structure makes them good examples of logs in the Scandinavian countries, and thereby suitable for the objective of this study.

The logs were scanned using a medical CT scanner (Siemens SOMATOM AR.T) and the resulting CT images show the log outer shape, as well as internal features such as pith location, heartwood border and knots. The knots are described by nine parameters specifying the knot geometry, position, and direction in the log (Oja 2000). All logs were scanned every 10 mm and the resulting images of each CT slice had 512 $\times$ 512 pixels with 12 bit gray scale values.

The description of log outer shape and knots in the ESSB makes it possible to simulate log breakdown of these logs.

2.2 Log breakdown simulation

Log breakdown simulation has the advantage that it can be carried out in a relatively short time frame and the input data can be processed an infinite number of times. This makes relative studies possible by comparing different methods or strategies on the same material. For these reasons it is widely used in the field of wood technology (Björklund and Julin 1998; Todoroki and Rönnqvist 1999; Nordmark 2005).

In this work the Saw2003 software (Nordmark 2005) was used since it is developed to interact with the data in the ESSB. This software has been validated both with respect to value and yield in previous studies (Chiorescu and Grönlund 2000). Within the software, the outer shape of the log is described by a cross section every 100 mm whereas knots are described using full information from the CT images (every 10 mm). The software performs simulation of cant sawing with curve sawing in the second saw, which are typical for sawmills in the Scandinavian countries. Figure 1 illustrates cant sawing, where the first sawing machine cuts the log into side boards and a cant. The cant is then rotated by 90 degrees and cut by the second sawing machine into side boards and center boards.

The breakdown simulations are controlled by setting the sawing patterns for the different log top diameter classes, the properties of the simulated sawing machine (e.g. kerf width), the grading rule settings, and the prices for center and sideboards of different grades. In the simulation of the sawing process, trimming and edging is value optimized with respect to the specified prices of the sawn timber. Only knots and wane are considered in this optimization.

2.2.1 *Grading*

In general, spruce side boards are not strength graded in Sweden due to the small cross section. Side boards of

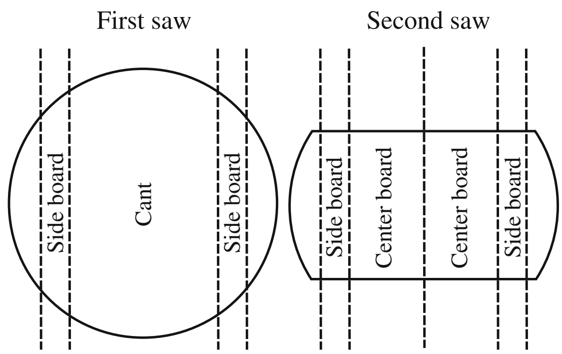

Fig. 1 Cant sawing. The first sawing machine cuts the log into side boards and a cant. The cant is then rotated by 90° and cut by the second sawing machine into side boards and center boards. Side boards are further processed by edging and trimming, while trimming is the only operation on center boards

spruce are also demanded for other types of products, such as outdoor claddings for example. Consequently, the side boards in this study were appearance graded using Saw2003. The grading of the simulated boards in Saw2003 is carried out according to appearance grading rules for knots and wane specified in the Nordic timber grading rules (Swedish Sawmill Managers association 1994). Knots and wane are the most important features for board grading in Scandinavia and this is why the majority of grading rules are related to these features. The Nordic timber grading rules separate the boards into three different grades, A, B and C, where grade A is considered as the best grade and grade C the worst. Consequently, market prices for grade A are higher than prices for grade B, etc. Boards not fulfilling the requirements for either of these grades are turned into chips in the simulation.

The center boards were outputted from Saw2003 and strength graded and trimmed according to the visual grading described in the Nordic standard INSTA 142 2009 using the software Matlab version R2012b. Timber graded according to the Nordic standard is divided into sorting classes T3, T2, T1 and T0 with corresponding strength classes C30, C24, C18 and C14. The numbers in these strength class names correspond to bending strength in MPa.

The grading was simplified and only carried out with respect to knots and wane on the boards since these defects are most important for appearance graded and strength graded timber. Information regarding other wood features such as annual ring width, splits, rot, resin pockets, top rupture etc. was not accounted for. Additionally, for the strength grading according to INSTA 142 2009, an arris knot lying completely or partly within wane should according to the standard be measured as an edge knot, but it was still measured as an arris knot. No special consideration was given to splay knots occurring as a consequence of top rupture.

The strategy investigated in this study was to produce center boards of sorting class T3 or T2. The center boards that did not fulfil the requirements for grade T3 or T2 were sold at a lower price.

2.2.2 *Sawing patterns, machine properties and prices*

The sawing patterns used in the simulations are shown in Table 1 where the logs, depending on their top diameter,

Table 1 Logs are sorted into a SC with respect to their top diameter. The first saw determines the width of the center boards and the thickness of the side boards in the first saw. The second saw determines the thickness of the center boards and additional side boards. All measures are nominal target values

SC	Sawing pattern (mm)	Top diameter range (mm)	Post first saw (mm)	Post second saw (mm)
1	38 by 100 by 2	130–149	19, 100, 19	19, 38, 38, 19
2	50 by 100 by 2	150–169	19, 100, 19	19, 50, 50, 19
3	50 by 125 by 2	170–184	19, 125, 19	25, 50, 50, 25
4	63 by 125 by 2	185–194	19, 125, 19	19, 63, 63, 19
5	50 by 150 by 2	195–209	19, 19, 150, 19, 19	19, 25, 50, 50, 25, 19
6	63 by 150 by 2	210–219	19, 19, 150, 19, 19	19, 25, 63, 63, 25, 19
7	50 by 175 by 2	220–229	19, 19, 175, 19, 19	19, 25, 50, 50, 25, 19
8	63 by 175 by 2	230–249	19, 19, 175, 19, 19	25, 25, 63, 63, 25, 25
9	63 by 200 by 2	250–264	19, 19, 200, 19, 19	25, 25, 63, 63, 25, 25
10	75 by 200 by 2	265–284	19, 19, 200, 19, 19	19, 25, 75, 75, 25, 19
11	75 by 225 by 2	285–304	19, 19, 225, 19, 19	19, 25, 75, 75, 25, 19
12	50 by 200 by 4	305–324	19, 25, 200, 25, 19	19, 25, 50, 50, 50, 50, 25, 19
13	50 by 225 by 4	325–344	25, 32, 225, 32, 25	25, 25, 50, 50, 50, 50, 25, 25
14	63 by 200 by 4	345–384	25, 32, 200, 32, 25	19, 25, 63, 63, 63, 63, 25, 19

were sorted into their respective sawing class (SC). The sawing allowance, e.g. shrinkage as well as deviations in the sawing, used in the simulation was set at 4 % of the nominal width for each board dimension and the saw kerf width was set to 4 mm for both the first saw and the second saw.

The prices per volume unit of sawn timber used were relative with respect to center boards of grade T2. In Table 2 the relative prices are presented for each grade. There is a steep drop from strength grades T3/T2 down to strength grade T1/T0/Reject. This is because spruce logs in northern Sweden in general are of high quality. If the sawn boards do not fulfil the requirements for strength grades T3/T2, they are used for products sold at a significantly lower price. The price drop from appearance grade A and B down to grade C is because spruce side boards of grades A and B are used for construction purposes, while side boards of grade C are used for packaging. The prices are representative for a sawmill in northern Sweden producing strength graded center boards and appearance graded side boards, according to industrial contacts. Unfortunately it was not possible to give a reference for prices of sawn timber in northern Sweden since they are not published due to competition between sawmills.

Table 2 Price list with price differentiation between board grades. The prices are relative to the price for center boards grade T2 as reference

Board type	Center boards					Side boards			Chips
Grade	T3	T2	T1	T0	Reject	A	B	C	–
Price/m^3	106	100	68	68	68	100	100	68	18

2.3 Simulation runs

Simulation of curve sawing of all logs in the ESSB was performed in each angle of rotation in the interval $[-90°, 90°]$, where the rotation angle of 0° corresponds to the horns down position. The term horns down refers to the log position in which a log with sweep (end-to-end curvature) is positioned so that the log ends are set down on the log carriage while the middle section of the log is off the carriage (Lundahl and Grönlund 2010). This log positioning prior to sawing is common practice in the Scandinavian sawmills when applying curve sawing.

The outcome of the simulations are two functions: the value recovery, V, and the volume yield, Y, of the boards as functions of rotation angle. These are defined as

$$V = f(\theta), \qquad \theta \in [-90°, 90°], \tag{1}$$

$$Y = g(\theta), \qquad \theta \in [-90°, 90°], \tag{2}$$

where θ is the log rotation angle and $\theta = 0°$ is set as the horns down position. The value function, V, and yield function, Y, with respect to the strength graded center boards of one example log are shown in Fig. 2. In the case where strength graded center boards, side boards and chips are considered, the value and yield functions look similar to the respective functions in Fig. 2.

Let θ_i^{max} be the rotational position of log i relative to horns down that maximizes the value. If there are N logs, the average value recovery relative to horns down is

$$\overline{V}_{rel}^{max} = \frac{1}{N}\sum_{i=1}^{N}\frac{V_i(\theta_i^{max})}{V_i(0)}. \tag{3}$$

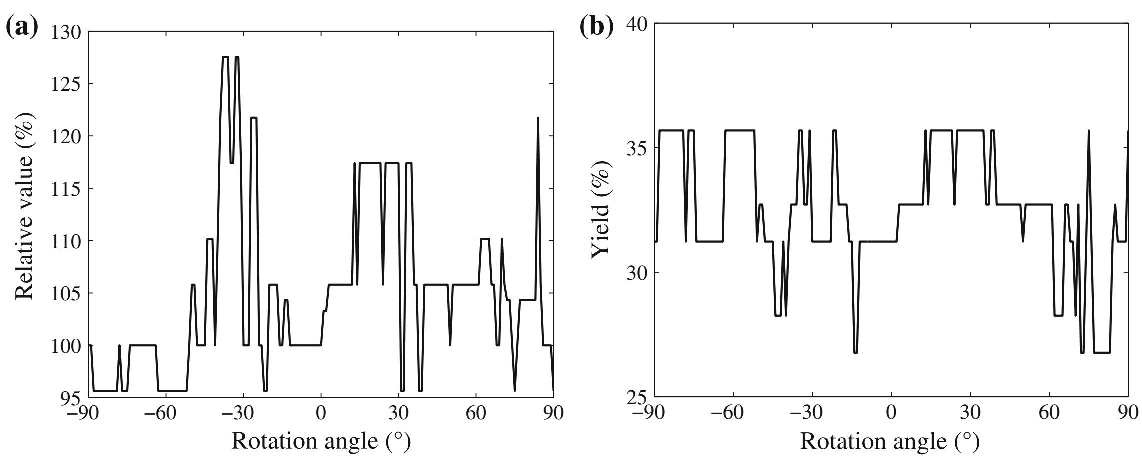

Fig. 2 Value function (**a**) and yield function (**b**) with respect to the strength graded center boards of a log. The value is relative to the value at the horns down position where the rotation angle of 0° corresponds to the horns down position

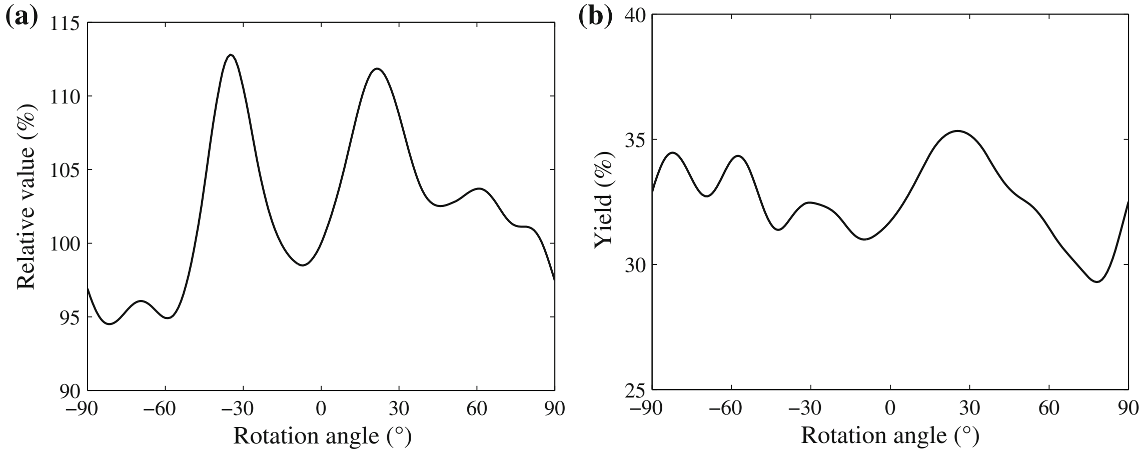

Fig. 3 The filtered value function (**a**) and the filtered yield function (**b**) obtained by applying a Gaussian filter to the value and yield function shown in Fig. 2a and b. The Gaussian filter had a standard deviation of $\sigma = 6°$ and a window size of $W_S = 35°$. The rotation angle of 0° corresponds to the horns down position

The average yield change for these choices of θ is calculated as

$$\overline{\Delta Y}_{V_{rel}^{max}} = \frac{1}{N}\sum_{i=1}^{N}\left(Y_i(\theta_i^{max}) - Y_i(0)\right). \qquad (4)$$

2.4 The effect of an error to the angle of rotation

A rotational error in a sawing machine is in this article assumed to be normally distributed $Z \in \mathcal{N}(\mu, \sigma)$, where μ is the expected value and σ is the standard deviation. In this study, the values of μ and σ were chosen as $\mu = 0°$ and $\sigma = 6°$, which are typical error levels for rotational error of a circular sawline in a Scandinavian sawmill (Heinola sawmill solutions 2014). An estimate of the expected value and yield function of a sawing machine with a rotational error from a distribution $Z \in \mathcal{N}(0°, 6°)$ was obtained using a Gaussian filter with $\sigma = 6°$ and window size $W_S = 6\sigma - 1 = 6 \cdot 6 - 1 = 35°$. Figure 3 shows an example of the effect of applying the Gaussian filter to the same value and yield functions as in Fig. 2.

3 Results

3.1 Center boards

Table 3 shows the resulting average value increase and yield change for center boards when simulating log breakdown in the value optimizing log rotation compared with the horns down position. The corresponding value for each SC is also shown as well as the results when a rotational error from a distribution $Z \in \mathcal{N}(0°, 6°)$ is present.

For an ideal rotation, the average value increase for all SC was 11 % compared with 6 % with a rotational error. The corresponding change in volume yield was 0 % on average both for an ideal rotation and with a rotational error. Histograms of center board value increase and yield change for optimizing log rotation in reference to horns down are shown in Fig. 4a and b. Figure 4(c) presents center board grade distribution for the rotational position that results in the optimum value of the center boards and for the horns down position. There was a shift of center board grades mainly from grade T1 at horns down position to grade T2 at the value optimized position.

3.2 Center boards, side boards and chips

Results when considering the total value of center boards, side boards and chips are shown in Table 3. The average value increases for an ideal rotation and with a rotational error applied were 11 and 5 %, respectively. Change in volume yield was 2 percentage points on average for an ideal rotation and 1 percentage point on average with a rotational error present. Histograms of value increase and yield change are presented in Fig. 5a and b. The grade distribution of the center boards for this case is shown in Fig. 5c.

Comparing the optimal rotational position between Figs. 4c and 5c, it is clear that the grade distributions of the center boards were almost unaffected when adding side boards and chips as parameters to the optimization. To better understand this result, tests were performed showing that for 281 out of the 677 logs (42 % of the logs), the optimal rotational positions with and without the addition of side boards and chips were identical. It is expected that

Table 3 Average value increase in percent and average yield change in percentage points in reference to horns down position and when choosing the log rotational position that maximizes the value of the center boards as well as the total value of all products (center boards, side boards and chips). Values both for an ideal and with an applied rotational error, $Z \in \mathcal{N}(0°, 6°)$, are presented. N is the number of logs in corresponding SC used in the simulations. The average value increase and average yield increase over all logs are the weighted means

		Center boards				All products			
		Average value increase (%)		Average yield increase (pp)		Average value increase (%)		Average yield increase (pp)	
SC	N	Ideal	With error	Ideal	With error	Ideal	With error	Ideal	With error
1	86	8	3	0	0	9	5	2	1
2	64	9	5	0	0	9	5	2	1
3	63	9	5	0	0	8	4	1	0
4	46	9	4	0	0	7	3	0	0
5	55	10	5	0	0	15	8	5	3
6	37	11	5	0	0	13	6	3	1
7	35	15	6	1	0	12	5	3	1
8	68	14	7	0	0	15	7	3	2
9	47	17	8	0	0	14	7	2	1
10	57	11	6	1	0	11	5	3	1
11	43	11	6	1	1	9	4	2	1
12	36	14	6	0	0	13	5	4	2
13	22	12	6	1	0	9	4	2	1
14	18	13	6	0	1	10	5	2	2
Total	**677**	**11**	**6**	**0**	**0**	**11**	**5**	**2**	**1**

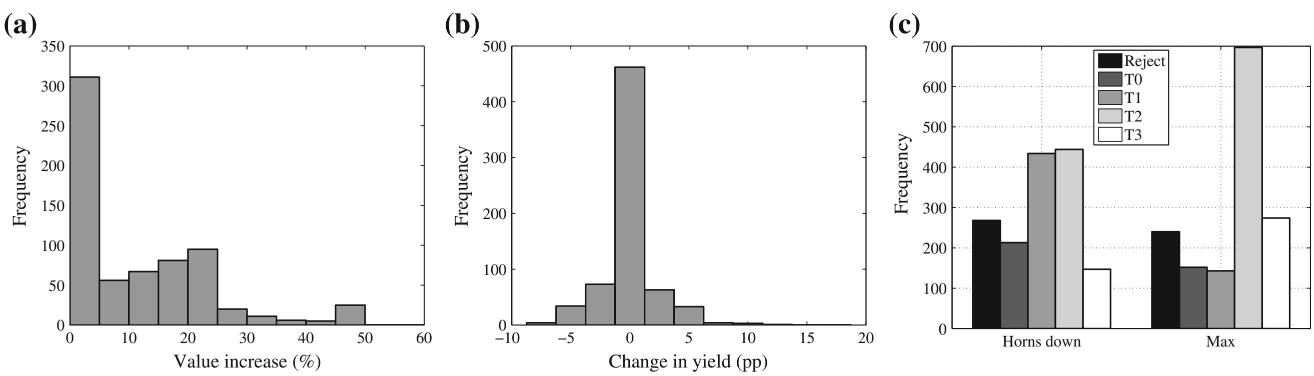

Fig. 4 Value increase in percent (**a**) and change in volume yield in percentage points (**b**) compared with the horns down position when simulating log breakdown in the rotational position that maximizes the value of the strength graded center boards. The grade distribution of the strength graded center boards for the horns down position and for the rotational position that maximizes the value of the center boards are shown in (**c**)

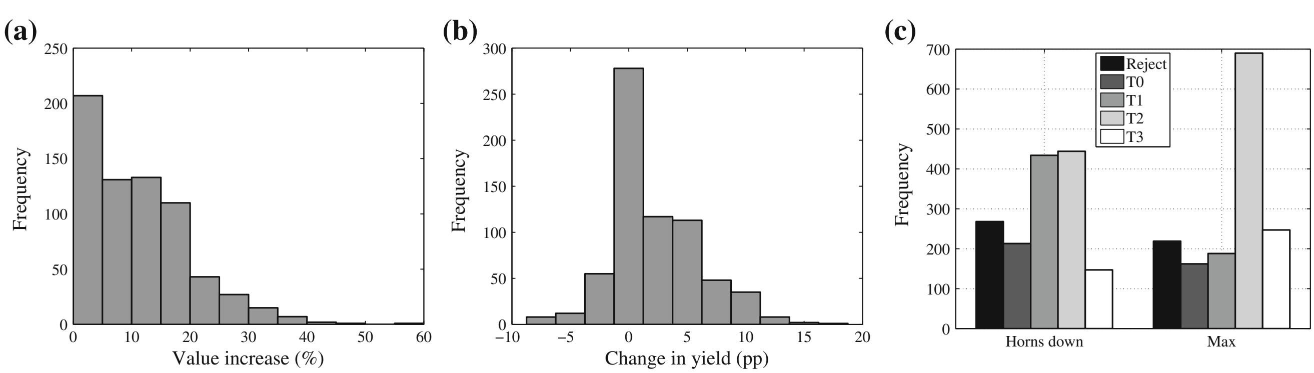

Fig. 5 Value increase in percent (**a**) and change in volume yield in percentage points (**b**) compared with the horns down position when simulating log breakdown in the rotational position that maximizes the total value of the strength graded center boards, appearance graded side boards and chips. The grade distribution of the strength graded center boards for the horns down position and for the rotational position that maximizes the total value are shown in (**c**)

the optimal rotational position would be the same for a large share of logs, since the volume of center boards is higher in relation to the volume of the side boards and thus affects the choice of optimal rotational position to the greatest extent. For the remaining 396 logs (58 % of the logs), there were just minor changes in the center board grade distribution even though there were changes in rotational position.

4 Discussion

A major discussion point is how the results of this simulation study can be applied to a Scandinavian sawmill sawing Norway spruce. This requires an understanding of how grading rules and price scenario affect the results. Also, practical considerations such as errors in log positioning and knot detection in CT images are important. In this section, these topics will be discussed together with the effects other wood properties and defects have on the results.

The results of this study are consistent with the results obtained by Berglund et al. (2013), where the boards were appearance graded according to the Nordic timber grading rules (Swedish Sawmill Managers association 1994). Both that set of grading rules and the strength grading rules used in this study (INSTA 142 2009) are based on knots visible on board surfaces. There are, however, some distinct differences between the two standards. For example, whether the knots are sound or dead and the position of knots are assessed differently depending on which of the two standards is used. This implies that the production strategy of using a CT scanner to rotate logs to their optimal position is robust for grading rules focused on knots.

Another result from Berglund et al. (2013) is that when increasing the price differentiation between grades, the value increase between horns down and the optimal rotational position becomes higher. This would likely be the effect in the current study as well. The grade distributions in Figs. 4c and 5c would be skewed toward T3 and T2 since it would be more profitable to produce boards of higher quality. Prices of sawn timber used in this study were obtained through industrial contacts, but prices vary both through time and between sawmills. However, the prices used in this study are a good reference point when investigating the profitability using different price levels.

No sawing machine is perfect when it comes to the positioning of the log when sawing. There are positioning errors in rotation, skew and lateral directions. From the simulations in this work, it is evident that a rotational error in the sawing machine reduces the average value increase, but that it is still profitable to rotate each log individually to obtain a higher value recovery. This means that a reduction in rotational error of the saw line results in a higher value recovery for a sawmill with a production strategy similar to the case in this study. This fact should put pressure on the manufacturers of sawing machines to reduce the positioning errors as much as possible. There are also errors in the detection of log features in the CT images, causing for example knots to be detected as larger or smaller than in reality. For appearance and visual strength grading rules, the detection of knots is the most important wood feature for the grade of the sawn boards. It was found in a study by Breinig et al. (2013) that knot detection errors of higher magnitudes than those reported by Johansson et al. (2013) still resulted in an improvement of value recovery when simulating a rotational optimization.

Another practical issue is that when curve sawing a crooked log and deviating from the horns down position, the sawn timber might be warped during the drying process. To better understand this, Fredriksson et al. (2014) investigated the effect that a rotational optimization would have on the warp of the sawn timber after drying. Half of their 177 studied logs were sawn in the horns-down position while the other half was sawn rotated perpendicular to horns down position. The later position is considered as the worse position when applying curve sawing and with respect to board distortions after drying, especially for curved logs. They found that for straight logs, with a bow height less than 15 mm, an unconventional rotational position did not cause excess spring in the boards. Bow and twist were not affected by the rotational position at all.

A limitation of the current study is that some defects and properties affecting the strength grade in INSTA 142 2009 are omitted in the current study. These include annual ring width, spiral grain and splay knots due to top ruptures. Splay knots is the most important defect of the three and if such knots appear on board surfaces, they have a large impact on strength grading. If splay knots are included in the simulations of this study, it is reasonable to expect that the difference in value would increase between the optimal rotational position and horns down. In other words, rotational optimization would be even more beneficial. The reasoning behind this is that for logs with top ruptures, the calculated total value of all sawn products would be lower if those top ruptures were accounted for when grading the boards. This applies to both horns down and the optimal rotational position, but in the latter case, information on top ruptures can be included in the optimization process. If horns down rotational position is used, the placement of splay knots will be purely random. When it comes to annual ring width and spiral grain, these properties and defects would likely have a limited impact on the results of this study. These properties do not vary in the same way as knots with respect to rotational position and would therefore affect boards sawn with different rotational positions to approximately equal extent.

All things considered, it seems to be profitable to use a CT scanner to rotate logs prior to sawing for a sawmill producing strength graded spruce boards. This holds even when various practical issues and error sources are considered. There are, however, several aspects of sawing real logs at a sawmill that differ compared with sawing their virtual counterparts in a simulator. The best way to validate the profitability of rotating logs to their optimal positions is to perform actual tests at a sawmill. A drawback of this compared with a simulation study is that a real log can only be sawn into boards once, hence no rotational optimization in reference to horns down based on CT data can be obtained for individual logs. However, such practical tests can be performed in other ways, for example by sawing a group of logs in the horns down position while another group of logs is sawn in their value optimizing position based on CT data. The difference in value outcome between the two groups could then be compared. Without access to an operational industrial CT scanner in a sawmill, such a study would however be very time-consuming. Simulation studies, such as described in the current paper, are therefore important in order to motivate more expensive studies.

5 Conclusion

The main conclusions of this article are that

- There is a possibility for Scandinavian sawmills producing strength graded spruce boards to increase their profitability by using a CT scanner to rotate logs prior to sawing.
- When using a CT scanner to optimize log rotation with respect to the value of visually strength graded center boards, appearance graded side boards and chips, the average value increase for the logs in this case study was 11 %.
- A normally distributed rotational error with expected value $\mu = 0^\circ$ and standard deviation $\sigma = 6^\circ$ reduced the average value increase to 5 %.
- The average value increase for the strength graded center boards only was 11 % for an ideal rotation and 6 % with a rotational error present.
- The main reason for the value increase is that the number of boards in sorting classes T2 and T3 was increased, while the number of boards in class T1 was reduced.

Acknowledgments This study was financially supported by the Swedish Governmental Agency for Innovation Systems (VINNOVA), WoodWisdom-Net, Fachagentur Nachwachsende Rohstoffe e. V. and participating companies.

References

Berggren G, Grundberg S, Grönlund A, Oja J (2000) Improved spruce timber utilisation (STUD). Tech. rep., Luleå University of Technology and AB Trätek, European shared cost research project within FAIR (DGXII/E2), contract no. FAIR-CT96-1915. Final report sub-task A 1.2. Database and non-destructive "Glass-log" measurements

Berglund A, Broman O, Grönlund A, Fredriksson M (2013) Improved log rotation using information from a computed tomography scanner. Comput Electron Agric 90:152–158

Björklund L, Julin B (1998) Value optimised cross-cutting and sawing of CT-scanned Scots pine stems. Tech. Rep. 48, Swedish University of Agriculture Sciences, Uppsala, Sweden, in Swedish

Björklund L, Moberg L (1999) Modelling the inter-tree variation of knot properties for Pinus sylvestris in Sweden. Studia forestalia Suecica 207

Breinig L, Berglund A, Grönlund A, Brüchert F, Sauter UH (2013) Effect of knot detection errors when using a computed tomography log scanner for sawing control. For Prod J 63(7/8):263–274

Chiorescu S, Grönlund A (2000) Validation of a ct-based simulator against a sawmill yield. For Prod J 50(6):69

Fredriksson M, Broman O, Persson F, Axelsson A, Ah Shenga P (2014) Rotational position of curved saw logs and warp of the sawn timber. Wood Mater Sci Eng 9(1):31–39. doi:10.1080/17480272.2013.853691

Giudiceandrea F, Ursella E, Vicario E (2011) A high speed CT-scanner for the sawmill industry. In: Divos F (ed) Proceedings of the 17th international non destructive testing and evaluation of wood symposium. University of West Hungary, Sopron, Hungary

Heinola sawmill solutions (2014) Circular sawline with optimizing profiling to Sweden, Norra Skogsägarna, Kåge, Sweden, 2010. http://www.heinolasm.fi/files/2812/9596/1791/HSM_kage_ENG.pdf, [Online; Accessed 02 Feb 2014]

INSTA 142, (2009) Nordic visual strength grading rules for timber. Swedish Standards Institute, Stockholm, Sweden

Johansson C (2003) Grading of timber with respect to mechanical properties. Timber engineering pp 23–43

Johansson E, Johansson D, Skog J, Fredriksson M (2013) Automated knot detection for high speed computed tomography on Pinus sylvestris L. and Picea abies (L.) Karst. using ellipse fitting in concentric surfaces. Computers and Electronics in Agriculture doi:10.1016/j.compag.2013.06.003, accepted for publication

Lundahl CG, Grönlund A (2010) Increased yield in sawmills by applying alternate rotation and lateral positioning. For Prod J 60:331–338

Nordmark U (2005) Value recovery and production control in the forestry-wood chain using simulation technique. PhD thesis, Luleå University of Technology, Luleå, Sweden

Oja J (2000) Evaluation of knot parameters measured automatically in CT-images of Norway spruce (*Picea abies* (L.) Karst.). Holz Roh Werkst 58:375–379

Swedish Sawmill Managers association (1994) Nordic Timber: grading rules for pine (Pinus sylvestris) and spruce (Picea abies) sawn timber: commercial grading based on evaluation of the four sides of sawn timber. Author, Sweden

Todoroki CL, Rönnqvist E (1999) Combined primary and secondary log breakdown optimisation. J Op Res Soc 50(3):219–229